Renewable and Sustainable Energy Reviews 30 (2014) 943–949

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Exploring temporal and spatial evolution of global energy production and consumption

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ARTICLE INFO

Article history:
Received 11 September 2013
Received in revised form
26 October 2013
Accepted 15 November 2013
Available online 7 December 2013

Keywords:
World energy supply
World energy consumption
Center of gravity

ABSTRACT

The purpose of this paper is to use a center of gravity theory to study the spatial distribution and centers of gravity for the global energy supply and consumption and to determine how they have changed over time. In 2011, Middle East was the biggest oil producer and Asia Pacific was the biggest oil consumer; Europe and Eurasia was the biggest natural gas producer and consumer; Asia Pacific was the biggest coal producer and consumer. The center of gravity for oil production is an overall movement towards the northeast. Compared with the shift of the center of gravity for crude oil production, that for oil consumption is an overall movement towards the southeast. The center of gravity for natural gas production and consumption moved towards the east. Our results also show that the center of gravity for coal production is an overall movement towards the southeast.

Contents

1. Introduction

Energy source is the basic element of socio-economic development. Energy supply and security has become the major issues of the development of human society and global political and economic pattern. Countries in the world have natural resource endowment conditions and different economic development level. Thus, energy supply and consumption of different countries also have some geographical differences. It is very meaningful to study temporal and spatial evolution of global energy supply and consumption, which can better know about how the center of the global energy supply and consumption has changed. To accomplish this purpose, the center of gravity theory is a useful tool.

The concept of a center of gravity was first used to study population problems in the United States by Hilgard [6]. That concept derives from physics, and represents the point at which the distribution would balance if it were represented by weighted points on a weight less line, plane, or sphere [10]. Nowadays, the concept of a center of gravity has been commonly used to study geographic distributions of many fields. Duan et al. [2] studied the characteristics and law of the population distribution evolution in the Changjiang River Delta since the beginning of the reform and open-up of China. Movement of the gravity of carbon emissions per capita was analyzed by Wang et al. [14]. Peng and Lin [13] analyzed the temporal and spatial evolution of SO_2 and industrial dust emissions of energy consumption. Fu et al. [4] utilized the model of regional gravity

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.11.027

center to study the consumption gravity center and economic gravity center of Xinjiang during 1965–2009. A spatially explicit ecosystem services value index and gravity model were used to explore spatial change and gravity center movement for ecosystem services value [5]. The theory has been used to study the movement of centers of gravity related to economic parameters [7,9]. Liang and Zhang [12] studied the measure and analysis on the spatial inequality of urban energy consumption in China.

Some researchers also utilized the theory of centers of gravity to study the temporal and spatial differences of energy consumption. Fesharaki [3] argued that Asia has become the center of gravity of the world energy system. Based on the theory of centers of gravity, the spatial distribution and the application prospects of coal resource, economic potentials were analyzed by Wang et al. [15]. Li et al. [11] studied the change of the spatial pattern of rural energy consumption in China. Zhang et al. [16] also utilized this theory measured how China's energy production and consumption centers changed from 1997 to 2009. So far many researchers have paid more attention to different aspects of world energy supply and consumption. The Hierarchical Partial Least Squares model (Hi_PLS) was used to study spatial differences and influencing factors of global energy consumption [8]. However, no study has been devoted to explore the spatial distribution and centers of gravity for the global energy supply and consumption. This paper attempts to analyze the temporal and spatial evolution of global energy supply and consumption based on the theory of centers of gravity.

The remainder of paper is organized as follows: Section 2 presents the gravity model and the related data in this paper. The main results are presented in Section 3. The conclusions drawn are summarized in Section 4.

2. Gravity model and data

The position of the center of gravity in year t, (X^t, Y^t), is expressed as follows,

$$X^t = \frac{\sum_{i=1}^{n} M_i^t \times x_i}{\sum_{i=1}^{n} M_i^t} \quad (1)$$

$$Y^t = \frac{\sum_{i=1}^{n} M_i^t \times y_i}{\sum_{i=1}^{n} M_i^t} \quad (2)$$

where M_i^t represents the property value of i region in year t; (x_i, y_i) is the coordinate of i region.

The spatial distribution and centers of gravity for world energy production consumption is analyzed. Since the capital is a country's economic and political center, this paper uses the longitude and latitude coordinates of each countries capital city represent the coordinate of its region. Each countries energy production and consumption represents the property value of a region. The position of the center of gravity is then calculated using a combination of the geographical coordinates of each country and their corresponding property value. The longitude and latitude coordinates of each country capital city come from Google Earth. The related data over 1965–2011 in this paper has been collected from the BP Statistical Yearbook ([1]). The energy data is measured in standard oil consumption in Mtoe (million tones of oil equivalent). This paper only considers three energy types: oil, natural gas, and coal.

3. Main results

3.1. Oil production and consumption

World oil production increased from 1567.87 Mtoe in 1965 to 3995.62 Mtoe in 2011, representing an annual average growth rate of 2.05%. In 1965, North America was the largest oil producer, followed by Middle East, Europe and Eurasia, S. and Cent. America. But the share of Asia Pacific in world oil production only accounted for 2.86% in 1965. However, Middle East, as the largest oil producer, produced 1301.41 Mtoe in 2011, which accounted for 32.57% of world oil production. The oil production share in the world is presented in Fig. 1, which shows that there is a substitution between the increasing shares of Middle East (from 26.70% in 1965 to 36.57% in 2011) and a decreasing share of North America (from31.22% in 1965 to 16.76% in 2011). Since 1979, the share of Middle East had presented a declining trend and reached the lowest point (18.46%) in 1985. During 1965–2011, the growth speed of crude oil production of Asia Pacific was the fastest, representing an annual average growth rate of 4.8%. Its share reached 9.71% in 2011.

In 2011, the world oil consumption reached to 4059.07 Mtoe from 1512.8 Mtoce in 1965, with an average annual growth rate of 1.1%. In 1965, North America was biggest oil consumer, followed by Europe and Eurasia, and Asia Pacific, as shown in Fig. 2. Since 2004, Asia Pacific has exceeded North America and become the biggest oil consumer. There is a clear substitution between the increasing shares of Asia Pacific (from 10.8% in 1965 to 32.4% in 2011) and Middle East (from3.1% in 1965 to 9.1% in 2011) and a decreasing share of North America (from 40.9% in 1965 to 25.2% in 2011) and Europe and Eurasia (from37.9% in 1965 to 22.1% in 2011). Over the period 1965–2011, annual average growth rate of Asia Pacific, Middle East, and Africa exceeded 4%.

Figs. 3 and 4 present the changes in the centers of gravity for world oil production consumption. During 1965–2011, the center of gravity for oil production was between 22.21W and 13.50E and between 28.55N and 30.09N. In contrast, the oil consumption

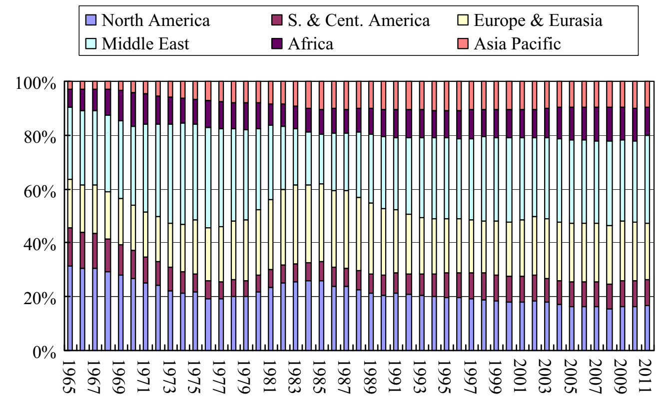


Fig. 1. Oil production share in the world.

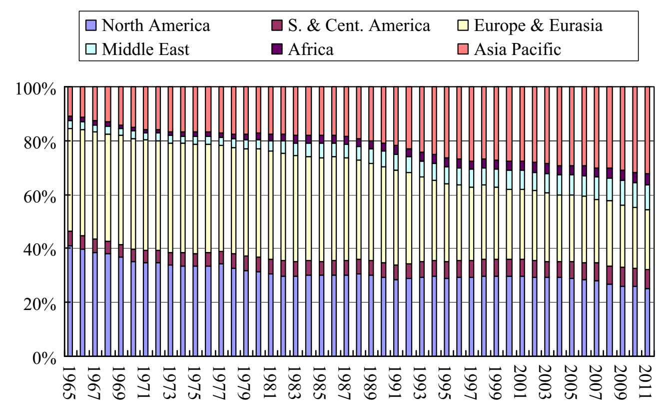


Fig. 2. Oil consumption share in the world.

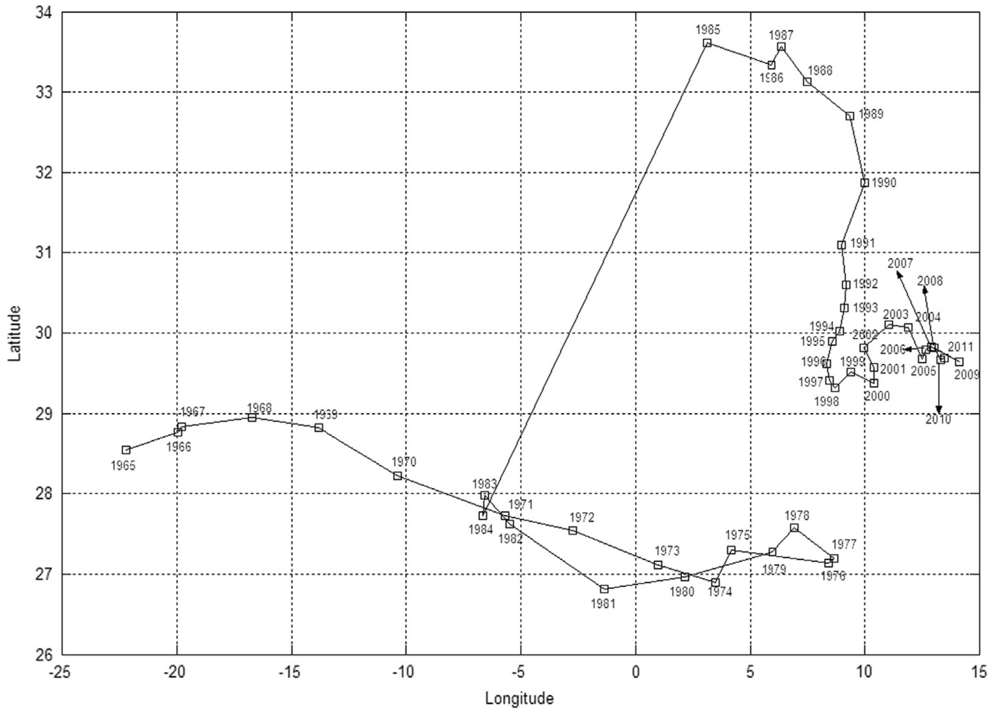


Fig. 3. Changes in the centers of gravity for oil production in world.

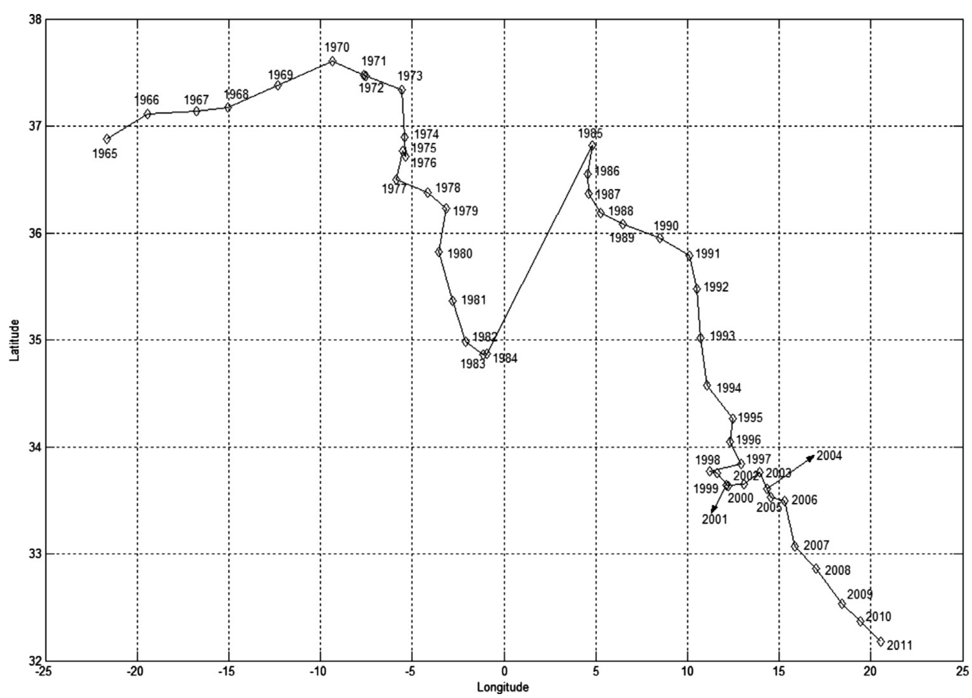


Fig. 4. Changes in the centers of gravity for oil consumption in world.

center of gravity was between 22.04W and 20.54E and between 37.28N and 32.18N.

Fig. 3 shows that the center of gravity for oil production is an overall movement towards the northeast. The oil production center of gravity moved from 22.21W and 28.55N in 1965 to 13.50E and 30.09N in 2011, a distance of 3456 km to the northeast, at an average rate of 75.13 km/year. The center of gravity for oil production moved toward southwest during 1965–1977, with the center moved from 22.21W and 28.55N in 1965 to 9.08E and 27.19N in 1977. Then that moved back to 7.05W and 28.13N in 1984. However, the center of gravity for oil production suddenly shifted northeast (3.11E and 34.01N) in 1985. Since 1985, the center of gravity moved gradually toward southeast. The centers of gravity for 20 years are located in the rectangle region (between 9.2E and 13.50E and between 31.0N and 30.09N)

Compared with the shift of the center of gravity for oil production, that for oil consumption is an overall movement towards the southeast, as shown in Fig. 4. The center of gravity for oil consumption moved from 22.04W and 37.28N in 1965 to 20.54E and 32.18N in 2011, a distance of 3905.55 km to the

northeast, at an average rate of 84.89 km/year. The center of gravity for oil consumption moved toward northeast during 1965–1970, with the center moved from 22.04W and 37.28N in 1965 to 9.34W and 38.01N in 1970. Then the center of gravity for oil consumption gradually moved toward southeast. In 1984, that reached 1.34W and 35.27N. However, the center of gravity for oil consumption suddenly shifted northeast (5.21E and 35.27N) in 1985. Since 1985, the center of gravity moved gradually toward southeast.

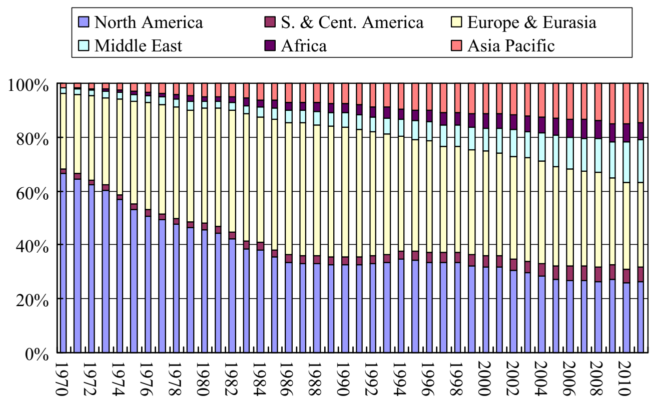


Fig. 5. Natural gas production share in the world.

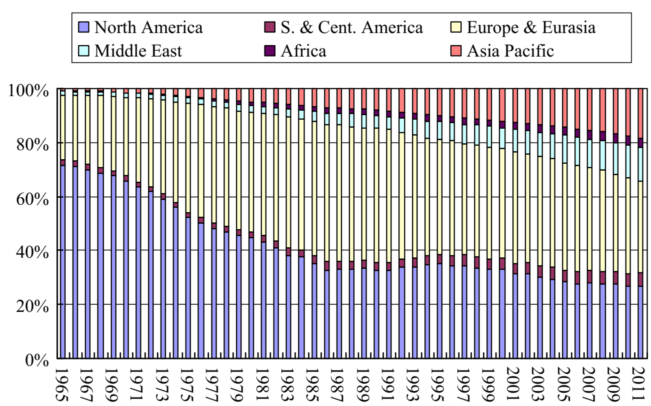


Fig. 6. Natural gas consumption share in the world.

3.2. Natural gas production and consumption

In 2011, world natural gas production climbed to 2954.77 Mtoe from 911.75 Mtoe in 1970, representing an annual average growth rate of 2.9%. In 1970, North America was the largest natural gas producer, followed by Europe and Eurasia. Those two regions accounted for 94.41% of world natural gas production in 1970. During 1970–2011, natural gas production share of North America declined from 66.58% to 26.53, as shown in Fig. 5. Since 1982, natural gas production share of Europe and Eurasia has exceeded that of North America and become the biggest producer. In terms of the annual growth speed of natural gas production, Africa is the fastest (10.9%), followed by Asia Pacific (8.69%), Middle East (8.31%), and S. and Cent. America (5.58%).

World natural gas consumption increased from 593.81 Mtoe in 1965 to 2905.62 Mtoe in 2011, representing an annual average growth rate of 3.51%. In 1965, North America consumed 425.37 Mtoe natural gas, which accounted for 71.63% of world natural gas consumption. Hereafter, the natural gas consumption share of North America gradually declined and reached to 26.92% in 2011, as shown in Fig. 6. In 1981, Europe and Eurasia exceeded North America and became the biggest natural gas consumer. In 2011, Europe and Eurasia consumed 34.1% of world natural gas consumption, followed by North America (26.92%), Asia Pacific (18.29%), and Middle East (12.48%). The natural gas consumption in Africa increased from 0.9 Mtoe in 1965 to 98.82 Mtoe in 2011. However, the average annual growth rate of Africa reached to 10.75%, followed by Asia Pacific (10.56%), Middle East (8.32%).

Figs. 7 and 8 present the changes in the centers of gravity for world natural gas production consumption. During the study period, the center of gravity for natural gas production

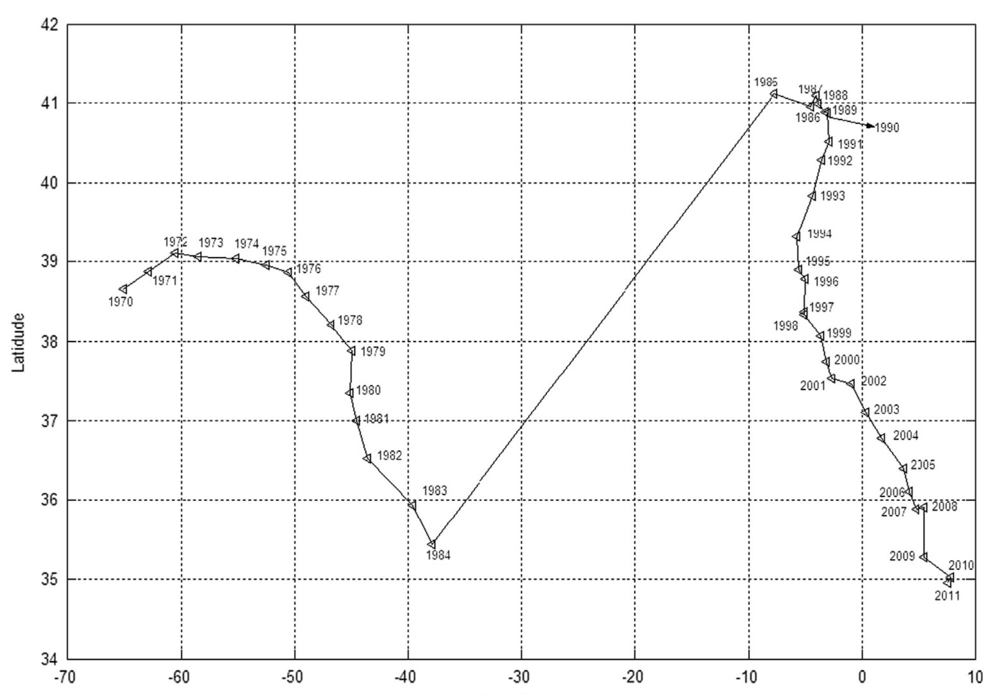


Fig. 7. Changes in the centers of gravity for natural gas production in world.

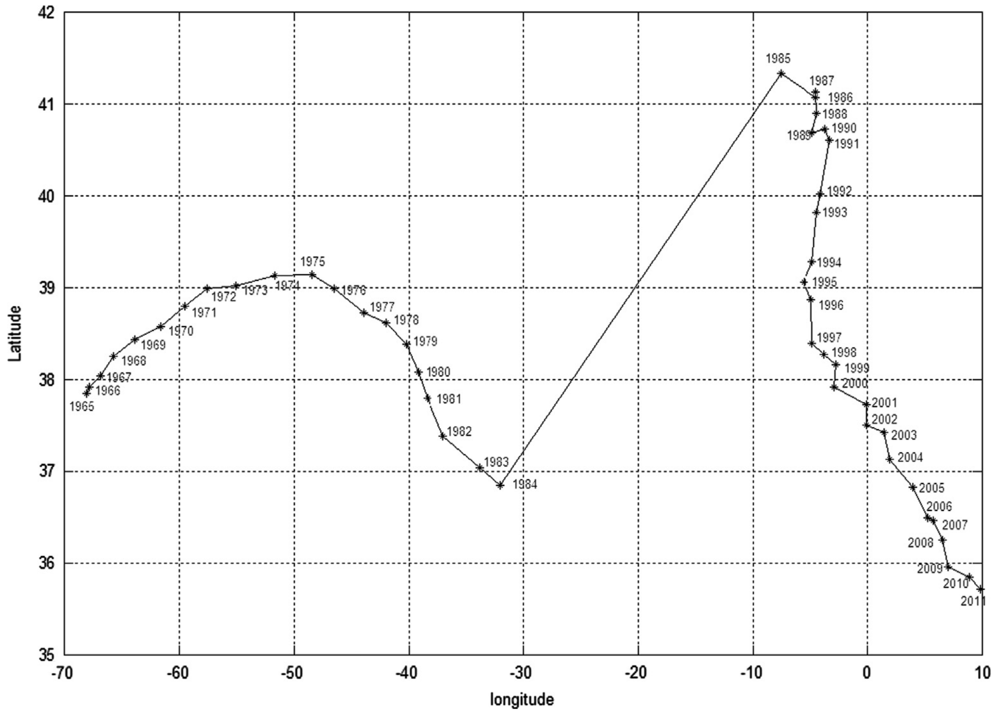


Fig. 8. Changes in the centers of gravity for natural gas consumption in world.

was between 65.01W and 10.29E and between 39.06N and 35.35N. In contrast, the natural gas consumption center of gravity was between 68.06W and 7.59E and between 38.24N and 36.11N.

Fig. 7 shows that the center of gravity for natural gas production is an overall movement towards the east and has three stages. The first stage is 1970–1984. In this period, the shift of the center of gravity for natural gas production shows an inverted U-shape. The center moved from 65.01W and 39.06N in 1970 to 38.27W and 35.44N in 1984. The second stage is 1984–1985. The center of gravity for natural gas production suddenly shifted northeast (8.07W and 41.12N) in 1985. The third stage is 1985–2011. Since 1985, the center of gravity moved sharply toward southeast. During 1970–2011, the natural gas production center of gravity moved from 65.01W and 39.06N in 1970 to 7.59E and 35.35N in 2011, a distance of 7487 km to the northeast, at an average rate of 182.60 km/year. Fig. 8 shows that the movement of the center of gravity for natural gas consumption is similar to that for natural gas production and has three stages. During 1965–2011, the natural gas consumption center of gravity moved from 68.06W and 38.24N in 1965 to 10.29E and 36.11N in 2011, a distance of 6731.28 km to the northeast, at an average rate of 146.32 km/year.

3.3. Coal production and consumption

World coal production increased from 1853.46 Mtoe in 1981 to 3955.46 Mtoe in 2011, representing an annual average growth rate of 2.55%. Europe and Eurasia was the biggest coal producer in 1981, which accounted for 42.4% of global coal production, as shown in Fig. 9. There is a substitution between the increasing shares of Asia Pacific (from 26.68% in 1981 to 67.91% in 2011) and a decreasing share of Europe and Eurasia (from42.4% in 1981 to 11.55% in 2011). Since 1994, North America exceeded Europe and Eurasia and became the secondary coal producer. During 1981–2011, Middle East produced small coal, and its share less than 0.02%. In 2011, Asia Pacific was the biggest coal producer, followed by North America (15.16%), Europe and Eurasia (11.55%), and Africa (3.7%).

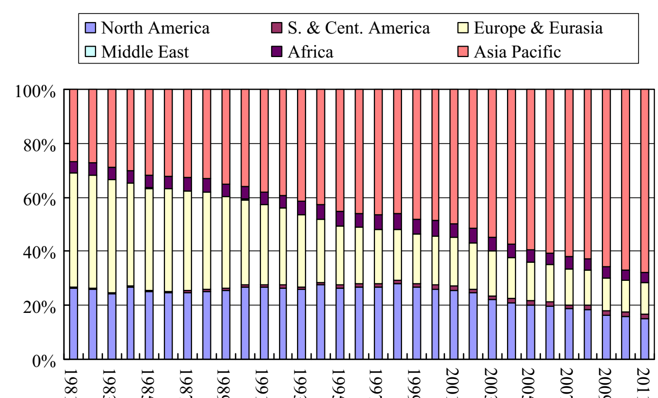


Fig. 9. Coal production share in the world.

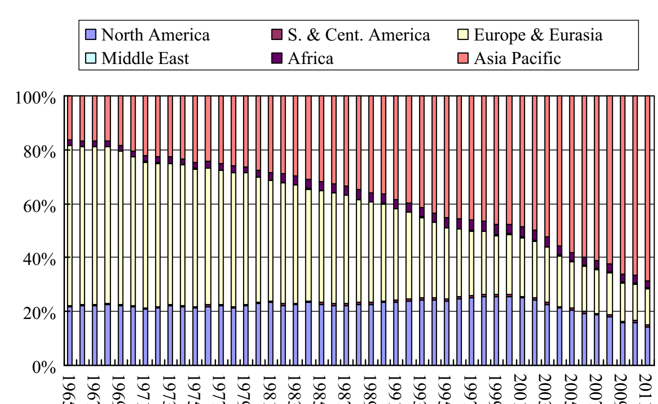


Fig. 10. Coal consumption share in the world.

World coal consumption increased from 1426.99 Mtoe in 1965 to 3724.34 Mtoe in 2011, representing an annual average growth rate of 2.1%. In 1965, Europe and Eurasia consumed 852.23 Mtoe

coal, which accounted for 59.72% of world coal consumption. North America was the secondary coal consumer and its share was 21.58, followed by Asia Pacific (16.31%). Hereafter, the coal consumption share of Europe and Eurasia gradually declined to 13.4% in 2011, as shown in Fig. 10. In 1981, Europe and Eurasia exceeded North America and became the biggest natural gas consumer. In 2011, Asia Pacific consumed 68.55% of world coal consumption, followed by North America (14.3%), Europe and Eurasia (13.4%), and Africa (2.6%). The coal consumption in Middle East increased from 0.21 Mtoe in 1965 to 8.66 Mtoe in 2011. During the study period, the share of Middle East was less than 0.05%. In terms of the annual growth speed of coal consumption, Middle East is the fastest (8.41%), followed by Asia Pacific (5.34%), S. and Cent. America (3.57%).

Figs. 11 and 12 present the changes in the centers of gravity for world coal production consumption. During 1981–2011, the center of gravity for coal production was between 16.30E and 70.30E and between 37.44N and 32.19N. In contrast, the coal consumption

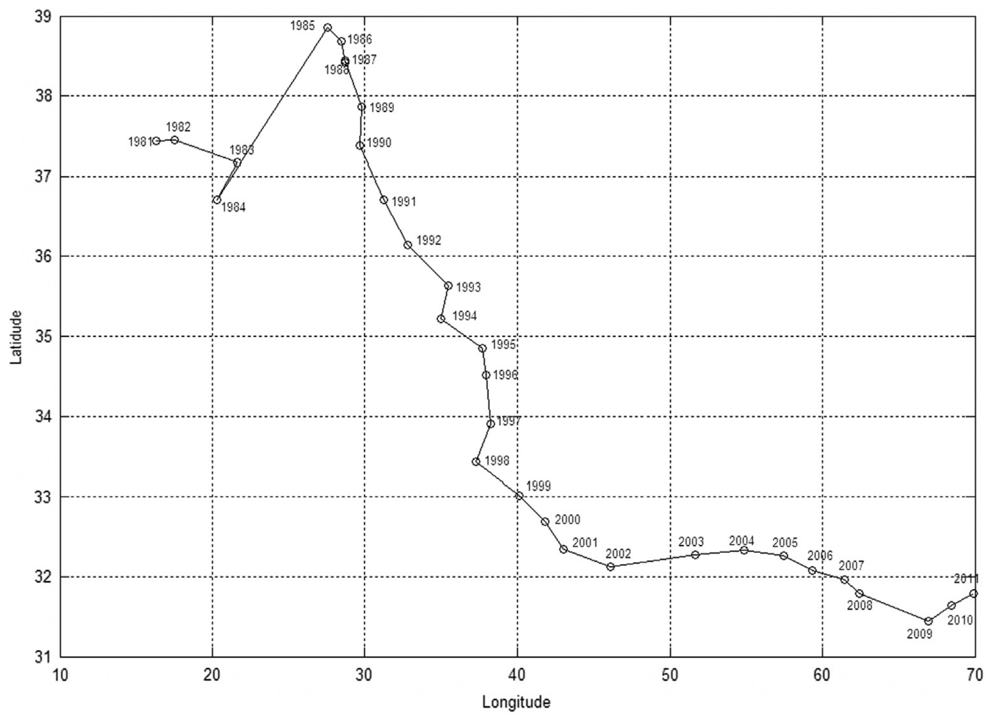


Fig. 11. Changes in the centers of gravity for coal production in world.

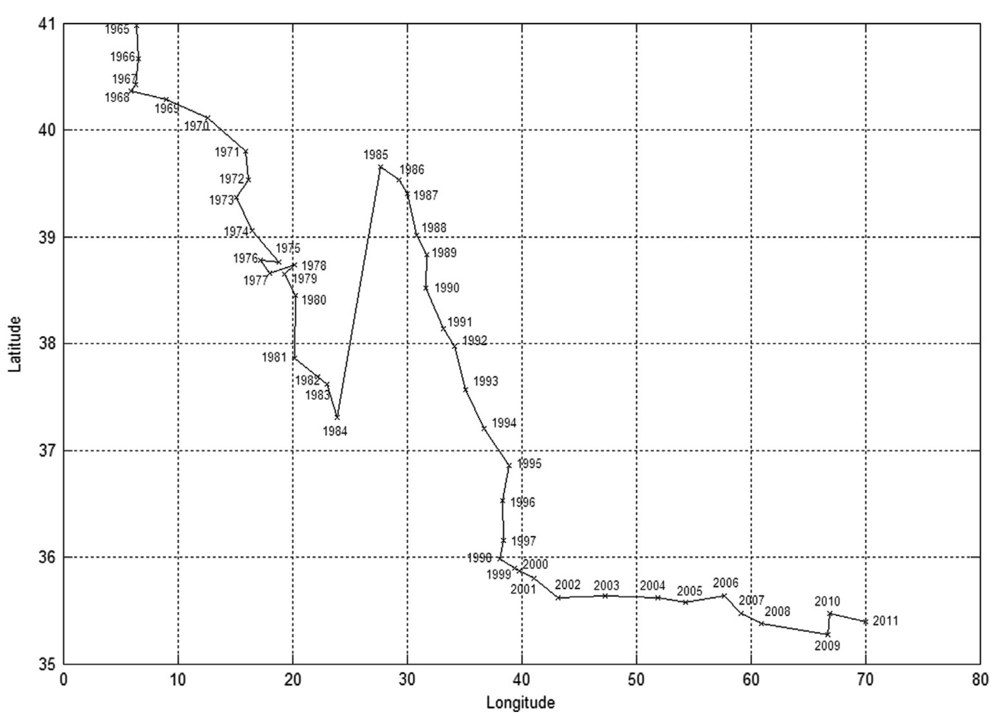


Fig. 12. Changes in the centers of gravity for coal consumption in world.

center of gravity was between 6.43E and 70.08E and between 41.38N and 35.39N.

Fig. 11 shows that the center of gravity for coal production is an overall movement towards the southeast and has three stages. The first stage is 1981–1985. In this period, the shift of the center of gravity for coal production shows a V-shape, which was located in a rectangle region (between 16.30E and 27.58E and between 37.44N and 39.35N). The second stage is 1985–2002. Since 1985, the center of gravity moved sharply toward southeast. The third stage is 2002–2011. The coal production center of gravity moved east from 46.12E and 32.12N in 2002 to 70.30E and 32.19N in 2011. During 1981–2011, the coal production center of gravity moved a distance of 4902 km to the southeast, at an average rate of 163.4 km/year. Changes in the centers of gravity for coal consumption in world are presented in Fig. 12. During 1981–2011, the movement of the center of gravity for coal consumption is similar to that of gravity for coal production. The center of gravity for coal consumption moved toward southeast during 1965–1984, with the center moved from 6.43E and 41.38N in 1965 to 24.35E and 37.31N in 1984. Over the period 1965–2011, the coal consumption center of gravity moved from 6.43E and 41.38N in 1965 to 70.08E and 35.39N in 2011, a distance of 5469 km to the northeast, at an average rate of 118.89 km/year.

4. Conclusions

Different countries are different in natural resource endowment conditions and economic development level. Thus it is interesting to study the spatial distribution and centers of gravity for the global energy supply and consumption. This paper utilizes the center of gravity theory to determine how they have changed over time.

In 2011, Middle East was the biggest oil producer. However, Asia Pacific accounted for 32.42% of global oil consumption. Europe and Eurasia was the biggest natural gas producer and consumer in 2011. Asia Pacific was the biggest coal producer and consumer in 2011. The center of gravity for oil production is an overall movement towards the northeast. Compared with the shift of the center of gravity for crude oil production, that for oil consumption is an overall movement towards the southeast. The center of gravity for natural gas production and consumption moved towards the east and also has three stages. Our results show that the center of gravity for coal production is an overall movement towards the southeast.

Acknowledgments

The authors gratefully acknowledge the financial support from the Fundamental Research Funds for the Central Universities (2012QNA38), the Philosophy and Social Science Foundation of Jiangsu Universities (2013SJD790061), the China Postdoctoral Science Foundation (2013M541752), and the Natural Science Foundation of Jiangsu Province (BK20130176).

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